

The effect of hidden color channels on nucleon-nucleon interaction

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In the framework of constituent quark model, the effect of hidden color channels on the nucleon-nucleon (NN) interaction is studied. By adjusting the color confinement strength between the hidden color channels and color singlet channels and/or between the hidden color channels and hidden color channels, the experimental data of S to I partial-wave phase shifts of NN scattering can be fitted well. The results show that the hidden color channel coupling might be important in producing the intermediate-range attraction of NN interaction. The deuteron properties and dibaryon candidates have also been studied with this model.

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I. INTRODUCTION

The study of nucleon-nucleon (NN) interaction has lasted over seventy years. The quantitative description of NN interaction has been achieved in the one-boson-exchange (OBE) models, the chiral perturbation theory (ChPT) and quark models. The $\chi^2/\text{dof} \sim 1$ for more than 2000 data has been obtained in meson exchange model [1, 2] and <2 in quark model [3].

In the OBE model [1], the long-range part of the NN interaction is attributed to one-pion-exchange. The short-range part is described by ρ, ω -meson exchange or phenomenological repulsive core. While the σ -meson exchange is responsible for the intermediate-range attraction. Phenomenological form factors are needed to achieve the quantitative description of the NN interaction data. In the chiral perturbation theory [2], the multi- π 's are exchanged between two nucleons. The short range part related to the nucleon internal structure is modeled by the contact terms with phenomenological low energy constants. The theory can give a quantitative description of the low-energy NN scattering below the π production threshold. It is hard to extend this model to higher energy, the very interesting resonance region of NN scattering.

With the advent of quantum chromodynamics (QCD), it is expected to describe the NN interaction from the fundamental degree of freedom of QCD, quark and gluon. Recently, lattice QCD calculation has achieved a qualitative description of NN interaction [4]. However it is still far from the quantitative description. The QCD-inspired quark models are useful in describing the NN interaction with the fundamental quark-gluon degree of freedom. The most popular and successful one is the constituent quark model. Where the non-perturbative (color confinement and spontaneous chiral symmetry breaking) and perturbative properties of QCD are incorporated into the model by introducing the phenomenological confinement potential, Goldstone-boson exchange and effective one gluon exchange between the massive constituent quarks [5]. Almost in all realistic quark models aimed to

describe the NN interaction, the short-range repulsion of NN interaction is described by one-gluon-exchange and quark anti-symmetrization. The long-range part is described by π -meson exchange which is the same as the OBE and chiral perturbation theory approaches. To describe the intermediate-range part, the σ -meson exchange is employed in most quark model approaches. The only one exception is the quark delocalization color screening model (QDCSM). Where the quark delocalization and color screening effect between interacting quarks within different quark clusters are employed [6] to describe the intermediate range attraction which is similar to the molecular covalent bond. To develop such a molecular covalent bond like model is because of the outstanding fact that the molecular force and nuclear force are similar except the energy and length scale difference [7]. Also because of the existence of σ meson is not sure for long. Recently BES collaboration reported the observation of σ -meson, which is appeared as $\pi\pi$ S -wave resonance [8]. However, the calculation of the correlated $\pi\pi$ exchange between two nucleons can not obtain enough attraction [9] as the phenomenological σ meson exchange did. The recent QDCSM calculation, on the other hand, showed that the quark delocalization and color screening mechanism is quantitatively equivalent to the phenomenological σ meson exchange in describing the NN intermediate range attraction [10]. In ChPT there is also no σ meson exchange. In addition, by introducing the multi-body color confinement interaction [11], or by incorporating the hidden color channels in the calculation [12], the intermediate-range attraction can also be obtained to some extent. Therefore the mechanism of the NN intermediate-range attraction is still an open question.

In this work, an alternative approach for NN interaction is studied. The hidden color channels ignored in the prevailing quark model calculations of NN interaction is included. Accordingly the confinement potential between different channels is modified as follows: the ordinary confinement is used for the quark-pairs within the same nucleon and the color singlet channels whereas a multiplying factor is introduced for the confinement po-

tential between the quark pairs if a hidden color channel is involved. The aim is to test if the color screening phenomenology used in QDCSM is an effective description of the hidden color channel coupling. The details of this model approach will be explained in next section. The NN scattering phase shifts obtained in this approach are confronted with experimental data and compared with ChQM and QDCSM approaches. The equivalence of these three quark models in describing the NN scattering data has been confirmed. The deuteron properties and dibaryon candidates are also studied with this model.

The structure of this paper is as follows. A brief introduction of three quark models used is given in section II. Section III devotes to the numerical results and discus-

sions. The summary is shown in the last section.

II. THREE QUARK MODELS

A. Chiral quark model

The Salamanca version of ChQM is chosen as the representative of the chiral quark models. It has been successfully applied to hadron spectroscopy and NN interaction. The model details can be found in Ref.[13]. Only the Hamiltonian and parameters are given here. The ChQM Hamiltonian in the nucleon-nucleon sector is

$$\begin{aligned}
H &= \sum_{i=1}^6 \left(m_i + \frac{p_i^2}{2m_i} \right) - T_c + \sum_{i<j} [V^G(r_{ij}) + V^\pi(r_{ij}) + V^\sigma(r_{ij}) + V^C(r_{ij})], \\
V^G(r_{ij}) &= \frac{1}{4} \alpha_s \lambda_i \cdot \lambda_j \left[\frac{1}{r_{ij}} - \frac{\pi}{m_q^2} \left(1 + \frac{2}{3} \sigma_i \cdot \sigma_j \right) \delta(r_{ij}) - \frac{3}{4m_q^2 r_{ij}^3} S_{ij} \right] + V_{ij}^{G,LS}, \\
V_{ij}^{G,LS} &= -\frac{\alpha_s}{4} \lambda_i \cdot \lambda_j \frac{1}{8m_q^2} \frac{3}{r_{ij}^3} [\mathbf{r}_{ij} \times (\mathbf{p}_i - \mathbf{p}_j)] \cdot (\sigma_i + \sigma_j), \\
V^\pi(r_{ij}) &= \frac{1}{3} \alpha_{ch} \frac{\Lambda^2}{\Lambda^2 - m_\pi^2} m_\pi \left\{ \left[Y(m_\pi r_{ij}) - \frac{\Lambda^3}{m_\pi^3} Y(\Lambda r_{ij}) \right] \sigma_i \cdot \sigma_j \right. \\
&\quad \left. + \left[H(m_\pi r_{ij}) - \frac{\Lambda^3}{m_\pi^3} H(\Lambda r_{ij}) \right] S_{ij} \right\} \tau_i \cdot \tau_j, \\
V^\sigma(r_{ij}) &= -\alpha_{ch} \frac{4m_u^2}{m_\pi^2} \frac{\Lambda^2}{\Lambda^2 - m_\sigma^2} m_\sigma \left[Y(m_\sigma r_{ij}) - \frac{\Lambda}{m_\sigma} Y(\Lambda r_{ij}) \right] + V_{ij}^{\sigma,LS}, \quad \alpha_{ch} = \frac{g_{ch}^2}{4\pi} \frac{m_\pi^2}{4m_u^2}, \\
V_{ij}^{\sigma,LS} &= -\frac{\alpha_{ch}}{2m_\pi^2} \frac{\Lambda^2}{\Lambda^2 - m_\sigma^2} m_\sigma^3 \left[G(m_\sigma r_{ij}) - \frac{\Lambda^3}{m_\sigma^3} G(\Lambda r_{ij}) \right] [\mathbf{r}_{ij} \times (\mathbf{p}_i - \mathbf{p}_j)] \cdot (\sigma_i + \sigma_j), \\
V^C(r_{ij}) &= -a_c \lambda_i \cdot \lambda_j (r_{ij}^2 + V_0) + V_{ij}^{C,LS}, \\
V_{ij}^{C,LS} &= -a_c \lambda_i \cdot \lambda_j \frac{1}{8m_q^2} \frac{1}{r_{ij}} \frac{dV^c}{dr_{ij}} [\mathbf{r}_{ij} \times (\mathbf{p}_i - \mathbf{p}_j)] \cdot (\sigma_i + \sigma_j), \quad V^c = r_{ij}^2, \\
S_{ij} &= \frac{(\sigma_i \cdot \mathbf{r}_{ij})(\sigma_j \cdot \mathbf{r}_{ij})}{r_{ij}^2} - \frac{1}{3} \sigma_i \cdot \sigma_j.
\end{aligned} \tag{1}$$

Where S_{ij} is quark tensor operator, $Y(x)$, $H(x)$ and $G(x)$ are standard Yukawa functions [3], T_c is the kinetic energy of the center of mass, α_{ch} is the chiral coupling constant, determined as usual from the π -nucleon coupling constant. All other symbols have their usual meanings. The parameters of this ChQM Hamiltonian are given in Table I.

B. Quark delocalization color screening model

The model and its extension were discussed in detail in Ref.[14, 15]. Its Hamiltonian has the same form as Eq.(1),

but without σ meson exchange and a phenomenological color screening confinement potential is used,

$$\begin{aligned}
V^C(r_{ij}) &= -a_c \lambda_i \cdot \lambda_j [f(r_{ij}) + V_0] + V_{ij}^{C,LS}, \\
f(r_{ij}) &= \begin{cases} r_{ij}^2 & \text{if } i, j \text{ occur in the same} \\ & \text{baryon orbit,} \\ \frac{1 - e^{-\mu r_{ij}^2}}{\mu} & \text{if } i, j \text{ occur in different} \\ & \text{baryon orbits.} \end{cases} \tag{2}
\end{aligned}$$

Here, μ is the color screening constant to be determined by fitting the deuteron mass in this model. The quark delocalization in QDCSM is realized by allowing the single particle orbital wave function of QDCSM as a linear

combination of left and right Gaussian, the single particle orbital wave functions in the ordinary quark cluster model,

$$\begin{aligned}
\psi_\alpha(\vec{S}_i, \epsilon) &= \left(\phi_\alpha(\vec{S}_i) + \epsilon \phi_\alpha(-\vec{S}_i) \right) / N(\epsilon), \\
\psi_\beta(-\vec{S}_i, \epsilon) &= \left(\phi_\beta(-\vec{S}_i) + \epsilon \phi_\beta(\vec{S}_i) \right) / N(\epsilon), \\
N(\epsilon) &= \sqrt{1 + \epsilon^2 + 2\epsilon e^{-S_i^2/4b^2}}. \\
\phi_\alpha(\vec{S}_i) &= \left(\frac{1}{\pi b^2} \right)^{3/4} e^{-\frac{1}{2b^2}(\vec{r}_\alpha - \vec{S}_i/2)^2} \\
\phi_\beta(-\vec{S}_i) &= \left(\frac{1}{\pi b^2} \right)^{3/4} e^{-\frac{1}{2b^2}(\vec{r}_\beta + \vec{S}_i/2)^2}.
\end{aligned} \tag{3}$$

The mixing parameter $\epsilon(S)$ is not an adjusted one but determined variationally by the dynamics of the multi-quark system itself. This assumption allows the multi-quark system to choose its favorable configuration in the interacting process. It has been used to explain the cross-over transition between hadron phase and quark-gluon plasma phase [16]. The model parameters are fixed as follows: The u, d -quark mass difference is neglected and $m_u = m_d$ is assumed to be exactly 1/3 of the nucleon mass, namely $m_u = m_d = 313$ MeV. The π mass takes the experimental value. The Λ takes the same values as in Ref.[3], namely $\Lambda = 4.2 \text{ fm}^{-1}$. The chiral coupling constant α_{ch} is determined from the πNN coupling constant as usual. The other parameters b , a_c , V_0 , and α_s are determined by fitting the nucleon and Δ masses and the stability of nucleon size b with the variation of quark mass m . All parameters used are listed in Table I. In order to compare the intermediate-range attraction mechanism, the σ meson exchange in ChQM and quark delocalization and color screening in QDCSM, the same values of parameters: b , α_s , α_{ch} , m_u , m_π , Λ are used for these two models. Thus, these two models have exactly the same contributions from one-gluon-exchange and π exchange. The only difference of the two models is coming from the short and intermediate-range part, σ exchange for ChQM, quark delocalization and color screening for QDCSM. To show the sensitivity of the QDCSM to the model parameters, the results of another set of model parameters (QDCSM2) is also reported.

C. Quark delocalization model with hidden color channels coupling (QDCCM)

This approach is focused on the hidden color channel effect which has been ignored almost in all quark model calculations but certainly should exist in a description based on the fundamental quark-gluon degree of freedom. In the lattice QCD calculation of NN interaction [4] these hidden color channels should have been included implicitly. However their effect has not yet been separated. We assume a Hamiltonian which is the same as that of QDCSM except that the usual quadratic con-

TABLE I: Parameters of three quark models discussed in this paper.

	ChQM	QDCSM1	QDCSM2	QDCCM
$m_{u,d}(\text{MeV})$	313	313	313	313
$b(\text{fm})$	0.518	0.518	0.60	0.518
$a_c(\text{MeV fm}^{-2})$	46.938	56.755	18.5	56.755
$V_0(\text{fm}^2)$	-1.297	-0.5279	-1.3598	-0.5279
$\mu(\text{fm}^{-2})$		0.45	1.00	
α_s	0.485	0.485	0.996	0.485
$m_\pi(\text{MeV})$	138	138	138	138
α_{ch}	0.027	0.027	0.027	0.027
$m_\sigma(\text{MeV})$	675			
$\Lambda(\text{fm}^{-1})$	4.2	4.2	4.2	4.2

finement

$$V^C(r_{ij}) = -ka_c \lambda_i \cdot \lambda_j (r_{ij}^2 + V_0). \tag{4}$$

is used but with an additional multiplying factor k . For the color-singlet channels (two baryon clusters are in the color-singlet states), the factor k takes the value 1. For the hidden color channels, two recipes are used. Recipe 1 (QDCCM1): For the coupling between hidden color channels and the color singlet channels, the factor k is taken as an adjustable parameter. All the other cases the factor k is kept 1. Recipe 2 (QDCCM2): The factor k is taken as adjustable parameter not only for color singlet-hidden color channels coupling but also for hidden color-hidden color channels. As for the single quark orbital wave function, the same form Eq.(3) as that of QDCSM is assumed. This model assumption is inspired by the lattice QCD calculation: The recent lattice QCD calculations show that the interactions among quarks are genuinely multi-body interactions. The color dependent two body confinement interaction is consistent with the lattice QCD results only for two and three quark systems in color singlet states but inconsistent with the multi-body interaction obtained in lattice QCD for multi-quark systems [17]. So the direct extension of the color dependent two body confinement interaction from two- or three-quark system to multi-quark system as used in the most quark model calculations is questionable. The calculation based on the direct extension can not describe the NN scattering quantitatively well even after including hidden color channels coupling as shown in QDCCM0 might be an indication of this inadequacy. In fact, for multi-quark systems and color octet nucleons, quark pairs are not always in color antisymmetric state but also color symmetric ones. The color factor $\lambda_i \cdot \lambda_j$ will give rise to anti-confinement interaction for symmetric quark pairs [18]. In QDCSM mentioned above, we used a color screening confinement interaction to model the effect of this multi-body confinement interaction obtained in lattice QCD. Here we study directly the effect of hidden color channel coupling to test if the phenomenological color screening confinement is an effective description of the hidden chan-

TABLE II: The channels used in NN scattering calculations and the factors k_1, k_2 (for recipes 1,2) for each channel ($I=1$).

J	channels	k_1/k_2
0	$^1S_0 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.42/1.39
	$^5D_0 : N\Delta, \Delta\Delta, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8$	
	$^3P_0 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.10/1.10
1	$^3P_1 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.35/1.28
2	$^1D_2 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	2.00/1.85
	$^5S_2(^5D_2) : N\Delta, \Delta\Delta, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8$	
	$^3P_2 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.75/1.66
	$^3F_2 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.00/1.00
3	$^3F_3 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.00/1.00
4	$^3F_4 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.00/1.00
	$^1G_4 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.00/1.00
	$^3H_4 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.00/1.00
5	$^3H_5 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.00/1.00
6	$^3H_6 : NN, N\Delta, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.00/1.00
	$^1I_6 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^2N_8 ^2\Delta_8, ^2N_8 ^2N_8$	1.00/1.00

nel coupling. In order to simplify the numerical calculation, a two body confinement interaction form Eq.(4) is still assumed but with an additional adjustable multiplying factor aimed to reflect the effect of the lattice QCD multi body confinement. At the same time, the model parameters are kept to the same as those of QDCSM1, except the color screening confinement form Eq.(2) is replaced by the usual quadratic confinement form Eq.(4). This is aimed to let the effect of hidden color channel coupling stand out.

III. THE RESULTS AND DISCUSSIONS

We calculated the NN scattering phase shifts of different partial waves (S, P, D, F, G, H and I waves) by three quark models mentioned above. To look for non-strange dibaryon resonances, a systematic calculation of NN scattering phase shifts with explicit coupling to $N\Delta$ and $\Delta\Delta$ channels is also done. The resonating-group

TABLE III: The channels used in NN scattering calculations and the factors k_1, k_2 (for recipes 1,2) for each channel ($I=0$).

J	channels	k_1/k_2
1	$^3S_1(^3D_1) : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	1.40/1.38
	$^7D_1 : \Delta\Delta, ^4N_8 ^4N_8$	
	$^1P_1 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^2N_8 ^2N_8$	1.80/1.70
	$^5P_1 : \Delta\Delta, ^4N_8 ^4N_8, ^4N_8 ^2N_8$	
2	$^3D_2 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	1.00/1.00
	$^7D_2 : \Delta\Delta, ^4N_8 ^4N_8$	
3	$^3D_3 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	2.40/2.20
	$^7S_3(^7D_3) : \Delta\Delta, ^4N_8 ^4N_8$	
	$^1F_3 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^2N_8 ^2N_8$	1.00/1.00
	$^3G_3 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	1.00/1.00
4	$^3G_4 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	1.00/1.00
5	$^3G_5 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	1.00/1.00
	$^1H_5 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^2N_8 ^2N_8$	1.00/1.00
	$^3I_5 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	1.00/1.00
6	$^3I_6 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	1.00/1.00
7	$^3I_7 : NN, \Delta\Delta, ^2\Delta_8 ^2\Delta_8, ^4N_8 ^4N_8, ^4N_8 ^2N_8, ^2N_8 ^2N_8$	1.00/1.00

method (RGM), described in more detail in

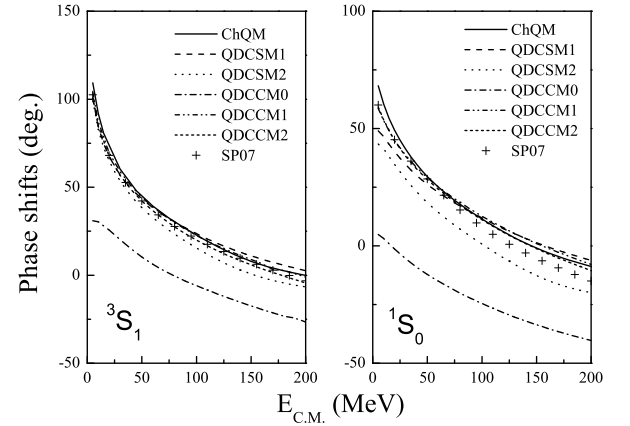


FIG 1. The phase shifts of NN S -wave scattering.

Ref.[19], is used to do the calculation. The experimental information used for the comparison is the partial-wave solution SP07 [20] of NN scattering data. For QDCSM,

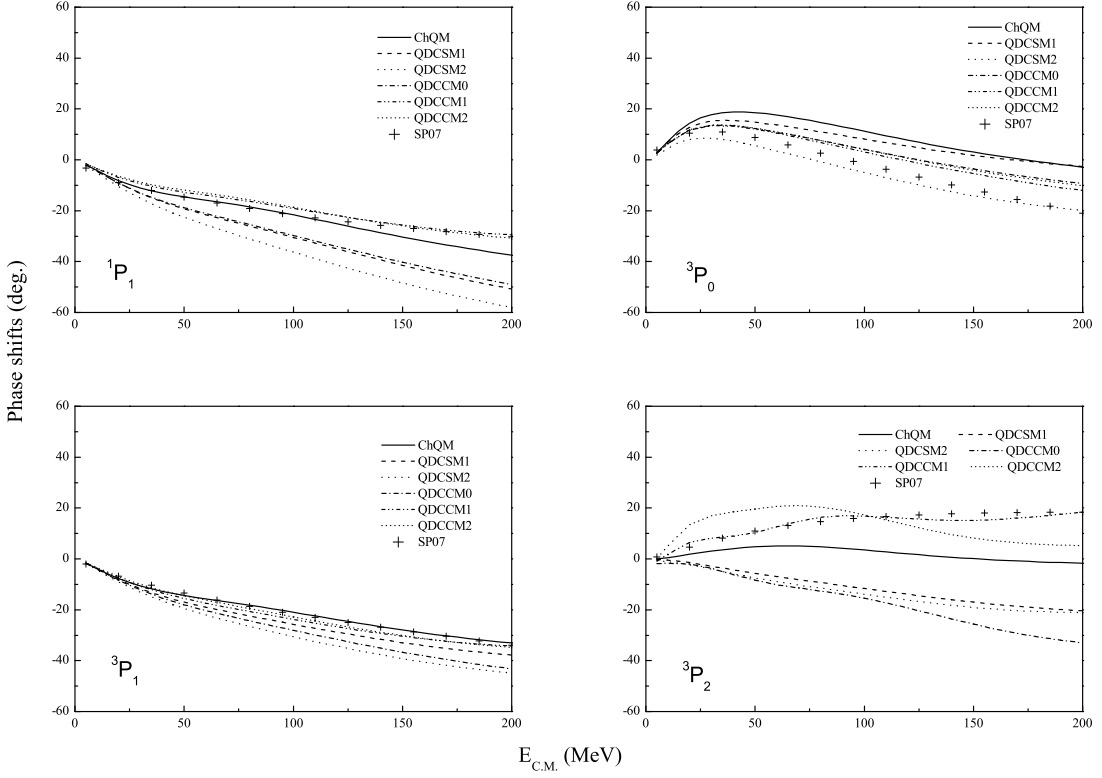


FIG. 2: The phase shifts of NN P wave scattering.

the color screening parameter μ is fixed by deuteron properties and no other parameters readjusted. For the third approach (QDCCM), the channels included in different partial waves are listed in Table II and III. The multiplying factors k_1, k_2 are adjusted to fit the NN phase shifts of SP07. The calculated results for NN scattering phase shifts are presented in section A; deuteron properties are shown in section B and the discussions of the dibaryon resonances are given in section C.

A. NN scattering phase shifts

(1) S -waves: Fig. 1 shows the NN scattering phase shifts for 3S_1 and 1S_0 partial waves. A perfect fit is obtained for both ChQM and QDCSM1 (QDCSM2 gives a little less attraction). The dominant contribution to the S -wave phase shift comes from the central part of the potentials. The agreement between two models means these two quark models give the same NN interaction, at least the same central part. For QDCCM, QDCCM1 and QDCCM2 also give good descriptions of NN 3S_1 and 1S_0 scattering phase shifts by including the hidden color channels and adjusting the color confinement interaction strength, while with the usual color confinement interaction strength ($k = 1$), the model (QDCCM0) calculated

phase shifts are far from the measured ones.

(2) P -waves: Fig. 2 shows the NN scattering phase shifts of 1P_1 , 3P_0 , 3P_1 and 3P_2 partial waves. For 1P_1 and 3P_1 , ChQM and QDCCM gave an almost perfect description of the experimental data. The 1P_1 phase shift is mainly determined by the central repulsion. The theoretical phase shifts of QDCSM and QDCCM0 are lower than experimental ones which show that these two models give a too strong repulsion. For 3P_0 , QDCSM2 described the experimental data better than others. For QDCCM we do not have to adjust the color confinement interaction strength a_c too much ($k = 1.1$ for both QDCCM1 and QDCCM2), so both QDCCM1 and QDCCM2, even QDCCM0, can fit the 3P_0 phase shifts reasonable well. ChQM and QDCSM1 give too strong attraction. For 3P_2 , QDCCM1 gives a perfect fit. ChQM, QDCSM and QDCCM0 do not have enough attraction. Fig. 3 shows central, spin-orbit and tensor components of the 3P_J phase shifts. Clearly, ChQM, QDCSM and QDCCM0 do not give strong enough attraction in the central and spin-orbit parts. In OBE, $\pi\rho$, $\pi\omega$ -exchange, which might have not been reproduced in the quark model calculations, are also needed to reproduce the P -wave phase shifts [1].

(3) D -waves: Fig. 4 shows the NN scattering phase shifts of 3D_1 , 3D_2 , 3D_3 and 1D_2 partial waves. For 3D_1 ,

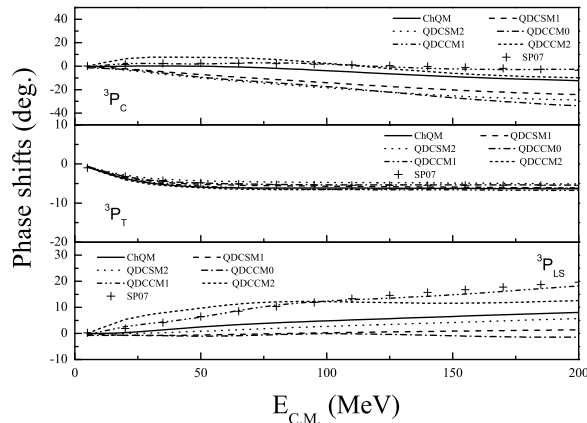


FIG. 3: Central, spin-orbit and tensor components of NN P wave scattering.

all the models fit the experimental data well except QDCCM0. For 3D_2 , QDCSM1 and QDCSM2 give a very good description of the experimental data (QDCSM2 is a little better), ChQM gives too strong attraction. For QDCCM, we find that we do not need adjust the color confinement interaction strength for this channel, QDCCM0 can fit the experimental scattering phase shifts. For 3D_3 and 1D_2 , ChQM described the experimental data better than QDCSM. For QDCCM, both adjusting recipes can give a perfect fit to the experimental data.

(4) F -wave: The calculated 1F_3 , 3F_2 , 3F_3 and 3F_4 NN phase shifts are shown in Fig. 5. For F wave scattering, we find that QDCCM0 already fit the experimental scattering phase shifts reasonably so we did not fine tune the confinement strength. All the models give a good description of the experimental data reasonably in the low energy region ($E_{c.m.} < 100$ MeV). Above 100 MeV, the model predictions deviate more or less from the experimental data. For 3F_2 QDCSM2 gave much better fit to the experimental data than QDCSM1, ChQM and QDCCM0. For 1F_3 , QDCSM1, QDCSM2 and QDCCM0 all give better fit to the experimental data than ChQM, especially at higher energy. However, for 3F_3 , ChQM is closer to the experimental data than other models. For 3F_4 , a perfect fit is obtained for QDCCM0, ChQM has a little too strong attraction at high energy and QDCSM gives a too weak attraction.

(5) G -wave: The NN phase shifts of 3G_3 , 1G_4 , 3G_4 and 3G_5 are shown in Fig. 6. All the models can describe the experimental data. We do not have to adjust the color confinement interaction strength for QDCCM here.

(6) H -wave: Fig. 7 shows the calculated 1H_5 , 3H_4 , 3H_5 and 3H_6 NN phase shifts. For H -wave phase shifts, all models fit to the experimental data equally well. We also find that we do not have to adjust the color confinement interaction strength for QDCCM here.

(7) I -wave: The calculated 3I_5 , 1I_6 , 3I_6 and 3I_7 NN phase shifts are shown in Fig. 8. For I -wave phase shifts,

all the models give almost the same results and fit the experimental data well. Again the color confinement interaction strength for QDCCM do not need to be adjusted here.

For high L partial waves, the long range π exchange dominates the interaction. Three quark models have the same π exchange and therefore they give almost the same results for $L \geq 3$ and we do not have to adjust the multiplying factor for the QDCCM for these high L partial wave.

These numerical results (Figs.1-8) show that by including the hidden color channels and adjusting the color confinement interaction strength, both adjusting recipes can fit the NN scattering phase shifts well. From the calculated S, P, D -wave phase shifts of NN scattering in QDCCM0, we can see that the attraction is always inadequate because of the appearance of anti-confinement interaction of symmetric quark pairs. By increasing the strength of confinement, the attraction coming from the confinement interaction is strengthened, QDCCM1 and QDCCM2 can give a good description of the experimental data. We take these results as an indication that the short and intermediate range NN interaction is caused by the nucleon internal structure and its distortion both in orbital and color spaces in the interacting process. These are quite the same as the atomic internal structure and its distortion in orbital space which give rise to the molecular covalent bond. The Anderson's conjecture [7] is verified here. The phenomenological color screening confinement might be an effective description of the hidden color channel coupling. The phenomenological σ meson exchange used in OBE and ChQM might be an effective description of the more complicated nucleon distortion in the NN interaction process as described in QDCSM and QDCCM. This mechanism also gives a natural explanation why does the NN interaction between two color singlet nucleons is so similar to the molecular interaction between two charge neutral atoms except the energy and length scale difference.

B. Deuteron

All these three models are used to calculate the properties of deuteron, the results are shown in Table IV. Both ChQM and QDCSM give a good description of deuteron. For QDCSM, by adjusting the color screening parameter, the same results for deuteron can be obtained for different baryon size b . Because of the large separation between the proton and neutron in the deuteron, the properties of deuteron mainly reflect the long-range part of the nuclear force. The same π -exchange used in the two models assure the properties of deuteron be fitted equally well. However π exchange alone can not provide strong enough intermediate-range attraction to make the deuteron bound. In ChQM, it is the phenomenological σ meson exchange which provides the intermediate range attraction. In QDCSM it is the quark delocal-

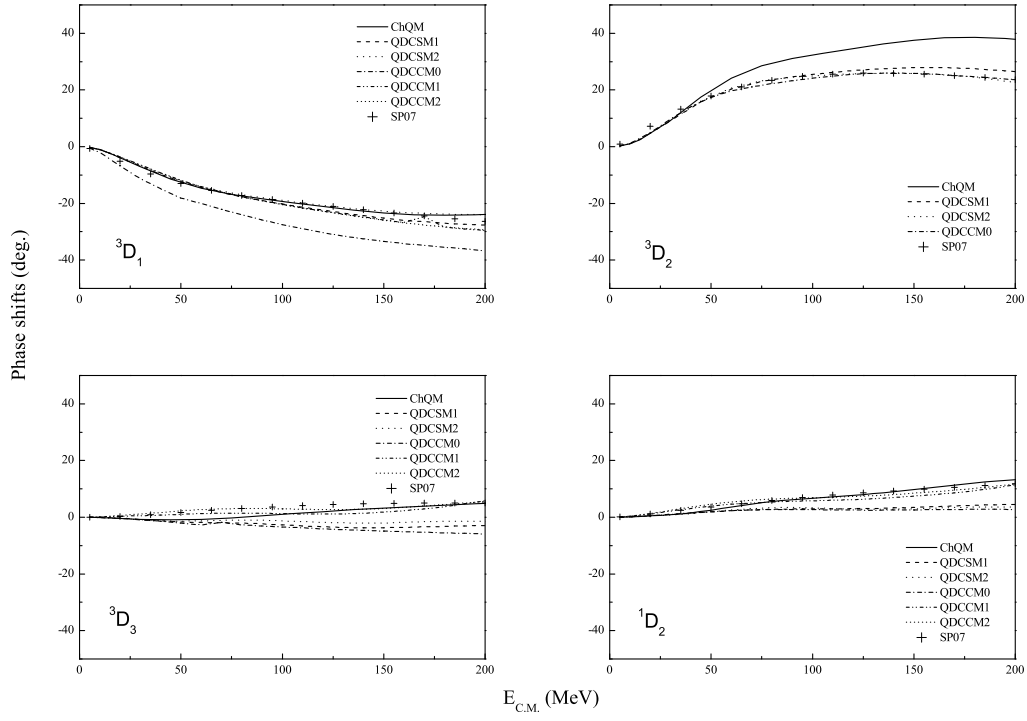


FIG. 4: The phase shifts of NN D wave scattering.

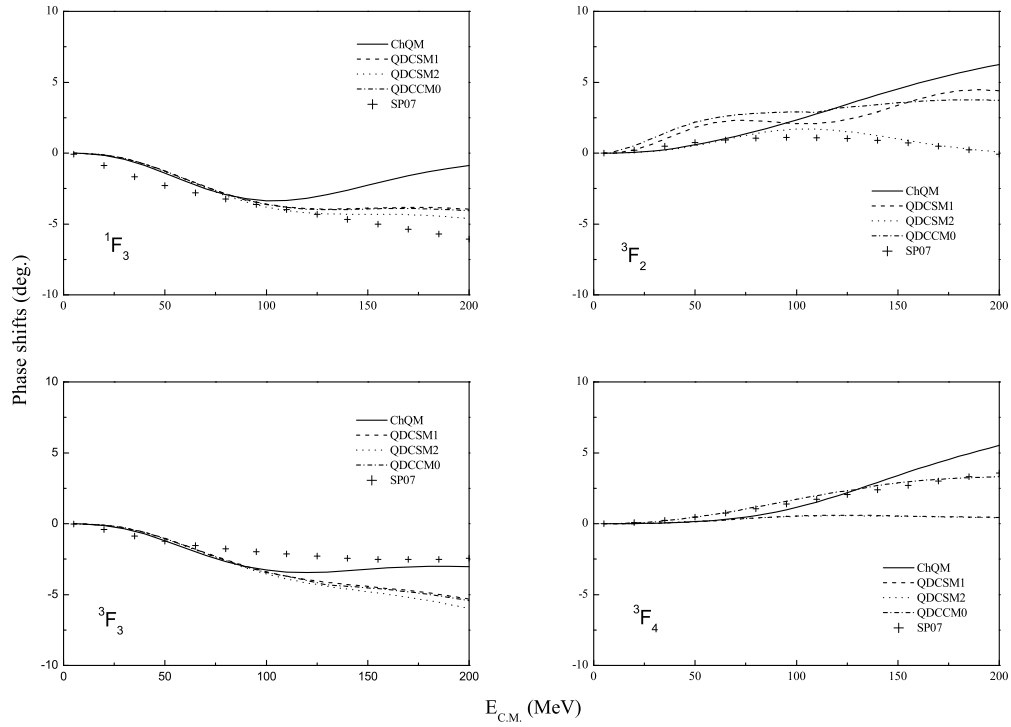
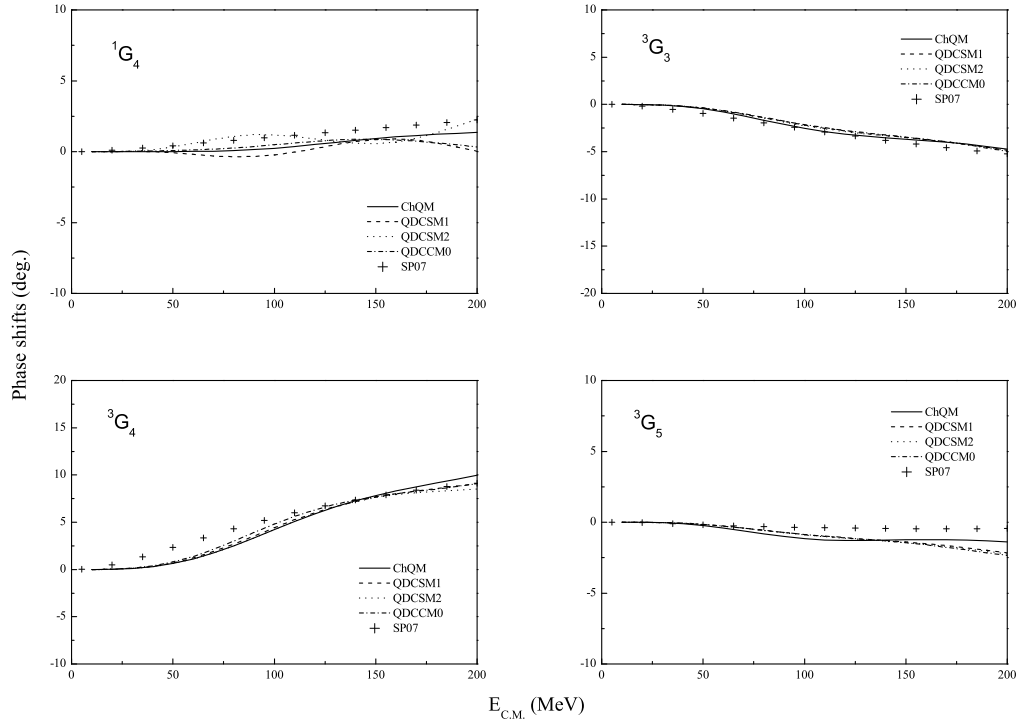
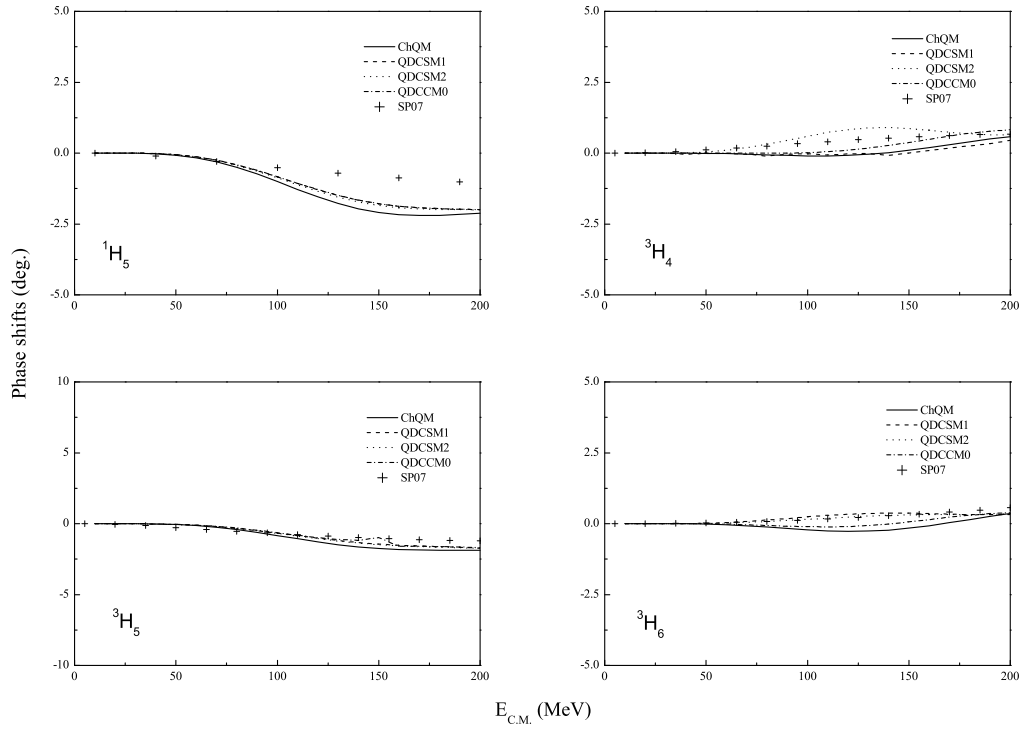
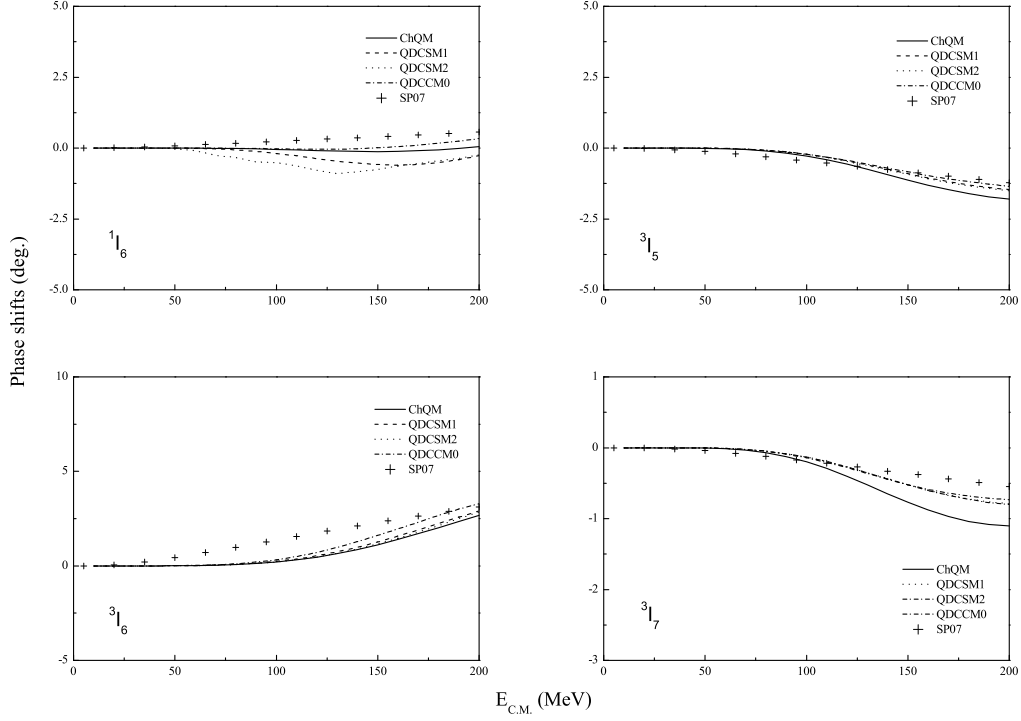


FIG. 5: The phase shifts of NN F wave scattering.

FIG. 6: The phase shifts of NN G wave scattering.FIG. 7: The phase shifts of NN H wave scattering.

FIG. 8: The phase shifts of NN I wave scattering.

ization and color screening which provide the intermediate range attraction. The fact that both models fit the deuteron properties well verifies once more that the two intermediate range attraction mechanisms used in these two models are equivalent.

Table IV shows that the binding energy and the D -wave component of deuteron can be reproduced (we didn't fine tune the strength of color confinement to get a better fitting). However the root mean square radius is too small in comparison to experimental value. This may indicate that QDCCM with the parameters giving in Table I gives rise to an NN scattering phase shift equivalent potential but a little too strong attraction in the short range region, which tightens up the deuteron.

TABLE IV: The properties of deuteron.

	ChQM	QDCSM1	QDCSM2	QDCCM1	QDCCM2
B (MeV)	2.0	1.94	2.01	1.0	2.2
$\sqrt{r^2}$ (fm)	1.96	1.93	1.94	1.2	1.1
P_D (%)	4.86	5.25	5.25	4.0	4.0

C. Dibaryon resonances in NN scattering

In this part, we show the results of a systematic search for the possible non-strange dibaryon candidates by three

quark models mentioned above.

The previous calculations [21] show that there are four possible dibaryons in the quark model calculations, $N\Delta$ state with $IJ = 12$, $\Delta\Delta$ states with $IJ = 01, 10, 03$. Here the QDCCM is applied to recalculate these states. All of these dibaryon states are allowed to decay via the NN channels. In other words, these dibaryon states appear as resonance states in the NN scattering process. So we calculate the NN scattering phase shifts by including all the possible channel couplings. The results are shown in Fig. 9.

(1) $I = 0, J = 1$: The 3S_1 energies of single $\Delta - \Delta$ channel calculation are lower than the corresponding threshold 100-350 MeV in ChQM, QDCCM and QDCSM. The coupling to the ${}^3S_1^{NN}$ channel has an unexpectedly large effect, pushing up the energy of ${}^3S_1^{\Delta - \Delta}$ state ~ 300 MeV, so that only in QDCSM2 it becomes a resonance at 2408 MeV. This very large mass shift is caused by the central interaction and the presence of a lower-mass state, the deuteron, in the admixed ${}^3S_1^{NN}$ channel. Mixing with other channels listed in Table III, the resonance mass is pushed down a little bit, to 2393 MeV. In ChQM and QDCCM, the 3S_1 energies in the single $\Delta - \Delta$ channel calculation are 100 MeV or more higher than that in QDCSM2. The additional large mass shift caused by the coupling to the NN channel then pushes the state above the $\Delta\Delta$ threshold. So no resonance appears in other models except QDCSM2. The phase shifts of ${}^3S_1^{NN}$ are shown

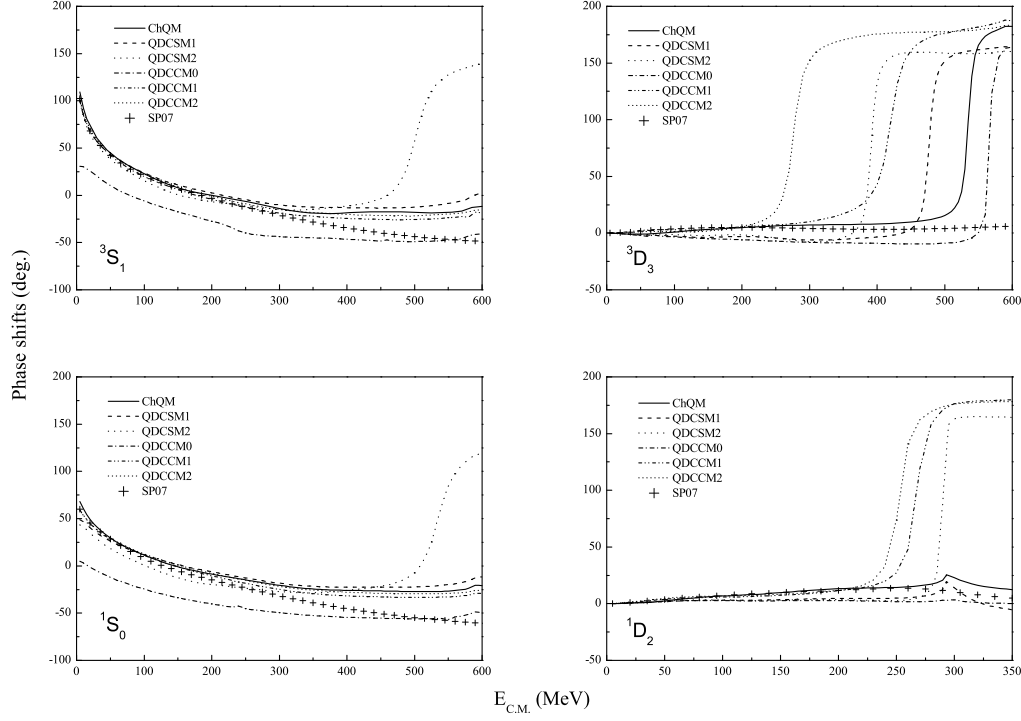


FIG. 9: The phase shifts of NN S wave and D wave scattering to energies beyond the $\Delta\Delta$ or $N\Delta$ threshold.

in the up left corner of Fig. 9, where the phase shifts for $100 < E_{c.m.} < 400$ MeV from ChQM, QDCSM1, QDCSM2, QDCCM1 and QDCCM2 agree with each other, as already pointed out in section A. The phase shifts of ${}^3S_1^{NN}$ rises through $\pi/2$ at a resonance mass only in QDCSM2. So, is there an $IJ = 01$ $\Delta\Delta$ resonance state with resonance mass 2393 MeV in the NN 3S_1 scattering channel is not sure.

(2) $I = 0, J = 3$: The single $\Delta - \Delta$ channel calculation shows that the state ${}^7S_3^{\Delta\Delta}$ is a bound state in all models used here. The coupling to the ${}^3D_3^{NN}$ channels causes this bound state change into an elastic resonance. The resonance mass shift, which is caused by the tensor interaction, is not large ~ 3 MeV. The calculation shows that the mass shift is always dominated by the NN scattering states below the bound-state rather than those above it. Coupling to other channels listed in Table III which are above the ${}^7S_3^{\Delta\Delta}$ bound state, the resonance is pushed down as expected. The calculated ${}^3D_3^{NN}$ phase shifts, shown in the up right corner of Fig. 9, rise through $\pi/2$ at the resonance masses in all models. But quantitatively the resonance masses are different in different models. The resonance mass in QDCSM1 is about 60 MeV lower than that in ChQM, and the QDCSM2 always has the lowest mass. For QDCCM, the resonance mass is 2443 MeV in QDCCM0, 2298 MeV in QDCCM1 and 2156 MeV in QDCCM2. This resonance ($IJ = 03$ $\Delta\Delta$) is a promising candidate for the observed isoscalar

ABC structure seen more clearly in the $pn \rightarrow d\pi\pi$ production cross section at 2.36 GeV in the recent report by the CELSIUS-WASA Collaboration [22].

(3) $I = 1, J = 0$: The ${}^1S_0^{\Delta\Delta}$ state is qualitatively similar to the ${}^3S_1^{\Delta\Delta}$ state, since they are just different spin-isospin states of the same quark system with the same relative orbital angular momenta. The calculated phase shifts, shown in the down left corner of Fig. 9, show that the resonance survives only in QDCSM2 after the channel coupling. The situation is almost the same as the ${}^3S_1^{NN}$ state.

(4) $I = 1, J = 2$: The phase shifts of NN scattering are shown in the down right corner of Fig. 9. From the curves, we find that a resonance appears in QDCSM2, QDCCM1 and QDCCM2. The resonance masses are: 2168 MeV in QDCSM2, 2144 MeV in QDCCM1 and 2130 MeV in QDCCM2. For ChQM and QDCSM1, only a prominent cusp appears at the $N\Delta$ threshold. Nevertheless, the state might correspond to the resonance looping in the Argand diagram of the 1D_2 pp -partial wave [23].

For odd-parity NN states, resonance poles are found for the isovector odd-parity NN partial waves 3P_2 , 3F_2 and 3F_3 [24]. These empirical resonance-like solutions reproduce the empirical Argand loopings of the partial wave solutions, but many studies in the past [25] have not resolved the question of whether these Argand loopings represent real dibaryon resonances. In our quark model calculation, we have not found any resonance at-

tributable to an $N\Delta$ or $\Delta\Delta$ bound state in the odd-parity NN states.

IV. SUMMARY

By including the hidden color channels and varying the strength of the color confinement potential between color-singlet channels and hidden color channels and/or hidden color channels and hidden color channels, a phenomenological quark model for baryon-baryon interaction is constructed. The model achieves a good description of S -, P -, D -, F -, G -, H -, I -partial wave phase shifts of NN scattering as good as other quark models. It also reproduces the binding energy and D-wave component of deuteron but a little too small root mean square radius. Applying the model to dibaryon search, similar results with QDCSM and ChQM are obtained. The results show that the hidden color channels are important for the NN intermediate range attraction. The lattice QCD calculations obtained the string like multi-body confinement interaction in the multi-quark system [17]. It is equivalent to the two body confinement Eq.(4) with $k = 1$ for a color singlet nucleon with three quarks. Oka extended the string-flip model to six-quark system and obtained a reasonable description of NN interaction [11] which might be viewed as a modeling of the lattice QCD string

like multi-body confinement. QDCCM fits the NN scattering data better and we suspect it might be another modeling of the lattice QCD multi-body confinement.

Certainly one would expect to directly use the string like multi-body interaction obtained in lattice QCD to calculate the NN interaction. However, it is not only because of the huge numerical task but also because there is no any information about the transition interaction between different string structure which hindered this approach.

Nuclear force is an old topic, it has been studied over 70 years and a large amount of experimental data has been accumulated. Although there are several approaches which can give almost perfect description of the experimental data, the mechanism for the intermediate-range attraction is still an open question. Lattice QCD achieved a qualitative description of the NN interaction already and it will finally achieves a quantitative description. But based on present lattice QCD technique it can not reveal the physical mechanism, for example to distinguish the phenomenological σ meson exchange and the nucleon distortion similar to molecular covalent bond mechanism for the intermediate range attraction. One has to develop the non-perturbative continuous QCD field theory method as well as non-perturbative QCD model to explore the NN interaction.

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